US010345837B1

(12) **United States Patent**
Valencia

(10) **Patent No.: US 10,345,837 B1**
(45) **Date of Patent: Jul. 9, 2019**

(54) **CURRENT-BASED FEEDBACK CONTROL FOR VOLTAGE REGULATORS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/958,967**

(22) Filed: **Apr. 20, 2018**

(51) **Int. Cl.**

H02M 3/156	(2006.01)
G05F 1/575	(2006.01)
H02M 3/157	(2006.01)
H03M 1/66	(2006.01)
G05F 1/62	(2006.01)
G05F 1/563	(2006.01)

(52) **U.S. Cl.**
CPC ***G05F 1/575*** (2013.01); ***G05F 1/563*** (2013.01); ***G05F 1/62*** (2013.01); ***H02M 3/157*** (2013.01); ***H03M 1/66*** (2013.01)

(58) **Field of Classification Search**
CPC G05F 1/614; G05F 1/618; G05F 1/613; G05F 1/42; G05F 1/607; G05F 3/12; H02M 3/156; H02M 3/1588; H02M 2003/1566; H02M 3/155; H02M 3/1582
See application file for complete search history.

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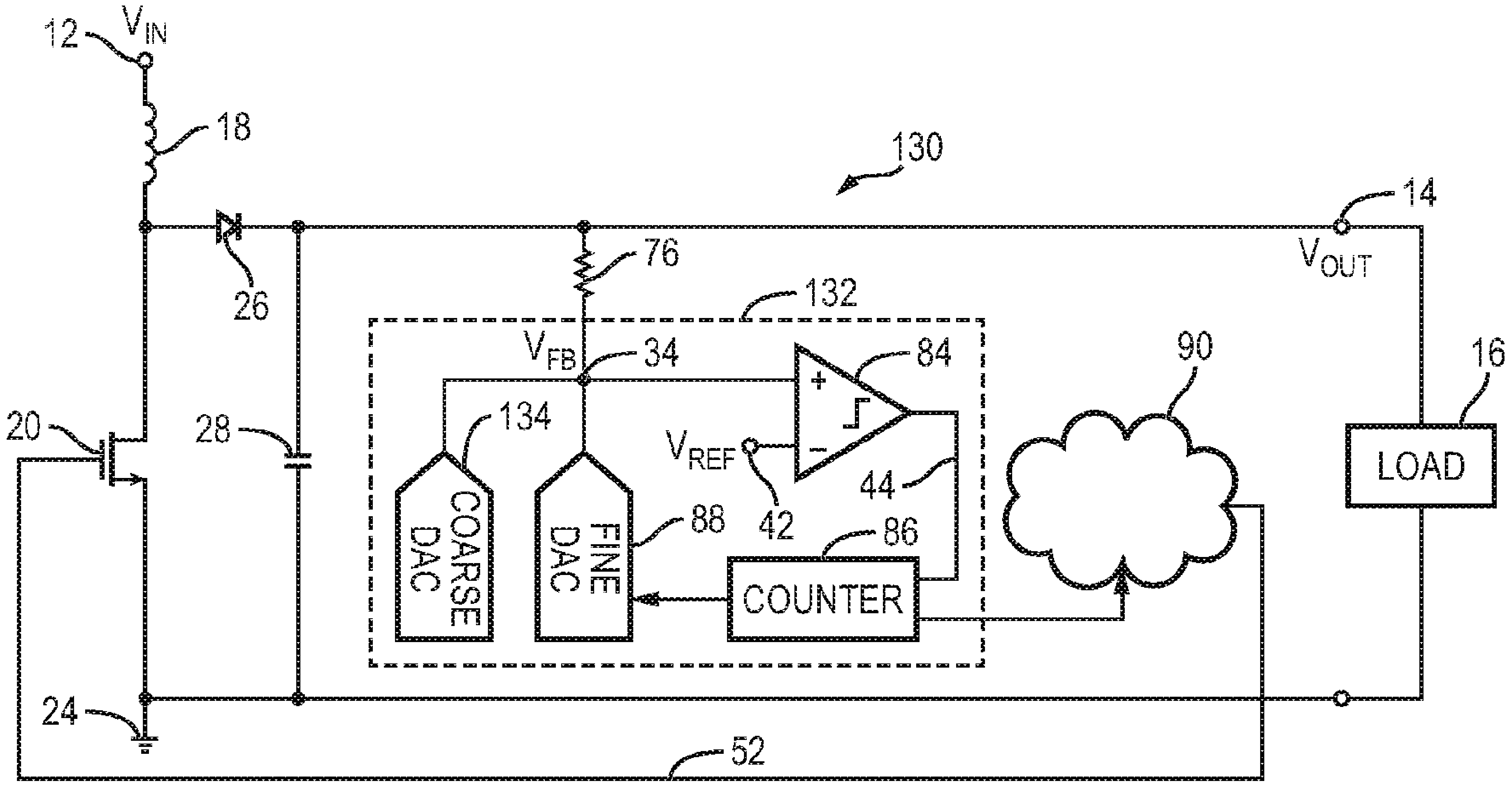
(57) **ABSTRACT**

A voltage regulator has a comparator and a reference voltage coupled to a first input of the comparator. An output voltage of the voltage regulator is coupled to a second input of the comparator through a resistor. A current source is coupled to the second input of the comparator. The first current source can be a first digital-to-analog converter (DAC). A second current source can be coupled in parallel with the first DAC. The second current source can be a second DAC. The voltage regulator can include a boost topology.

20 Claims, 5 Drawing Sheets



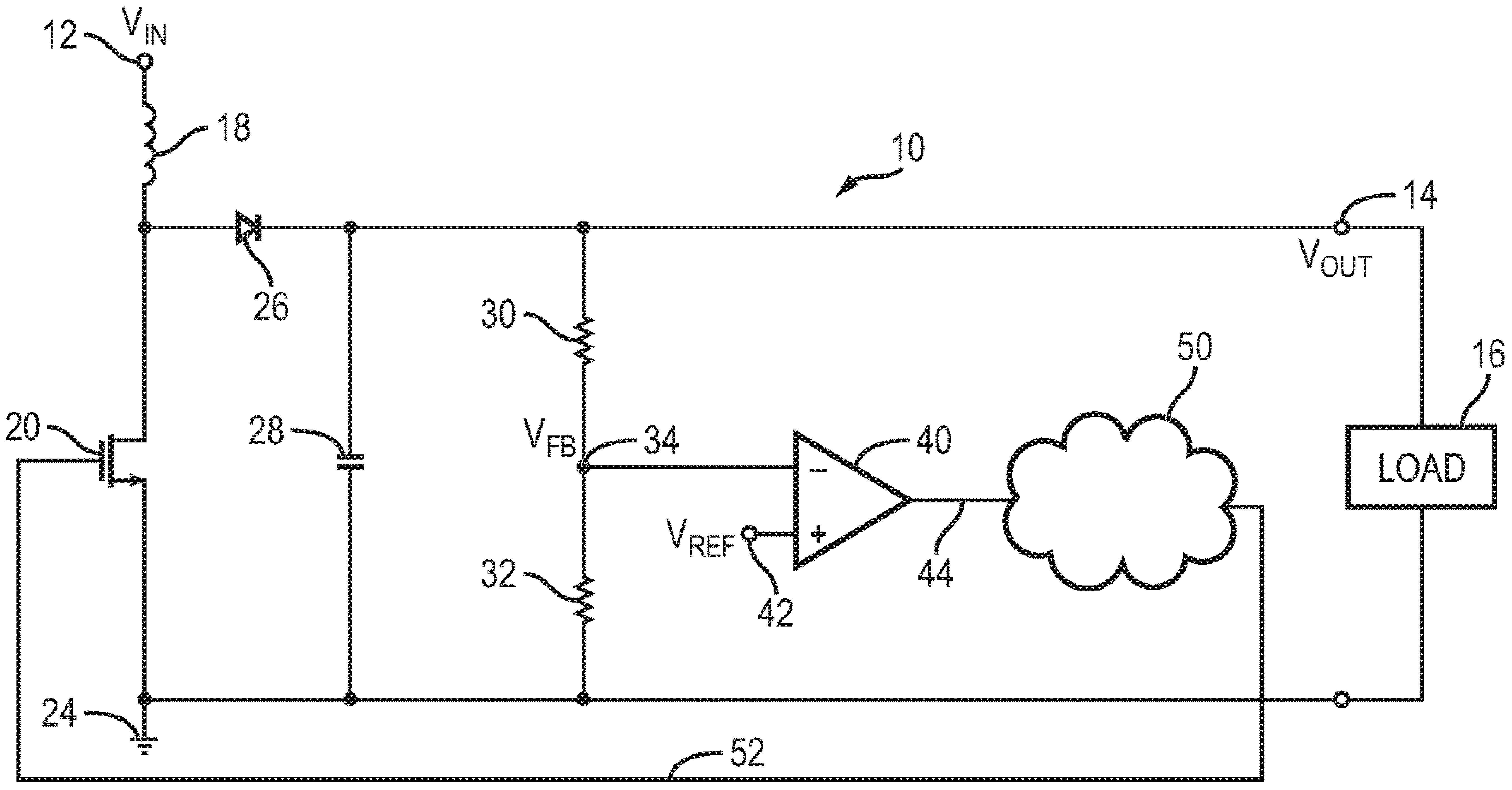


FIG. 1
(PRIOR ART)

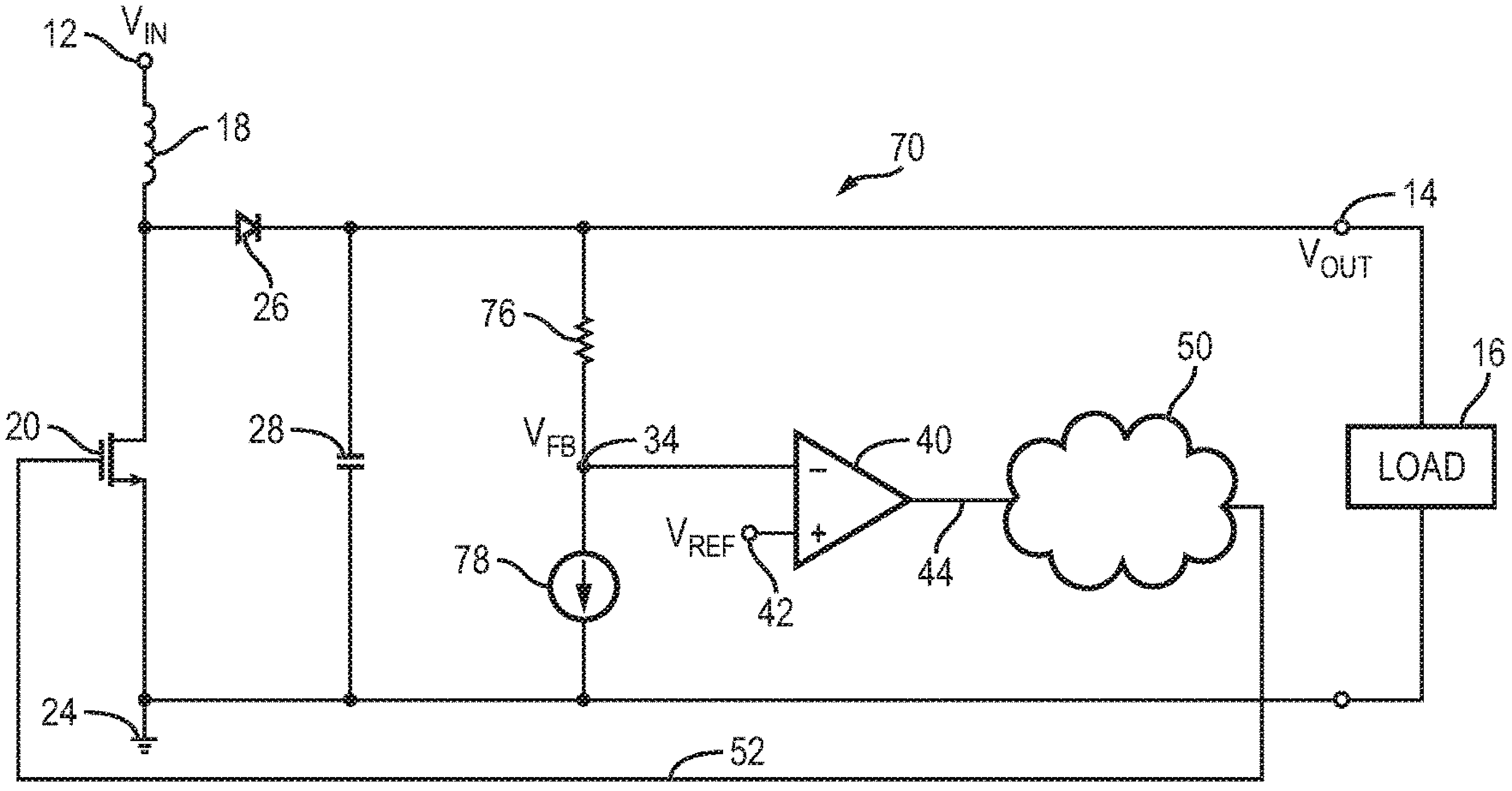


FIG. 2

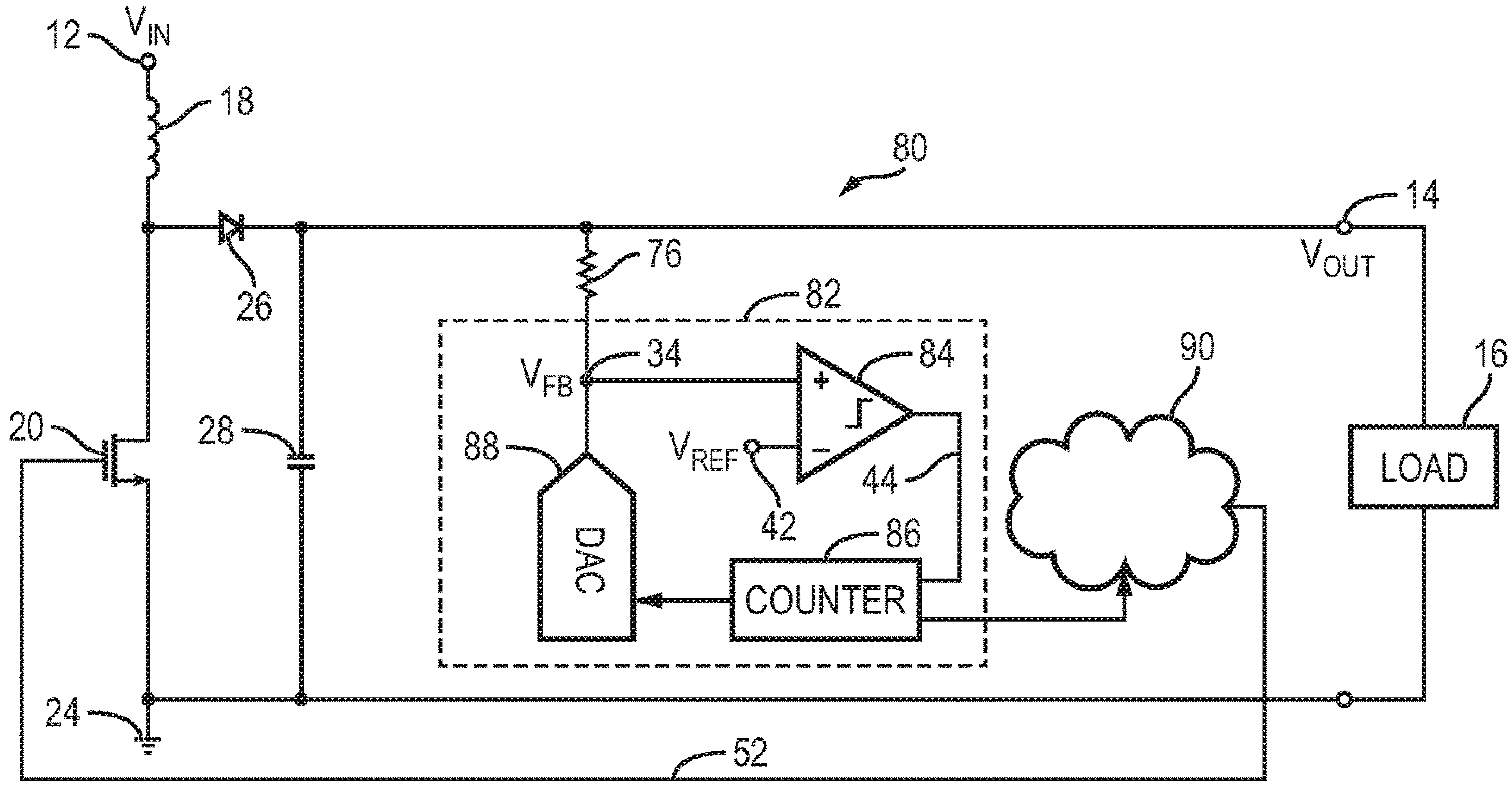

12
V_{IN}
18
80
14
V_{OUT}
76
26
82
V_{FB}
34
84
90
16
LOAD
20
28
88
V_{REF}
44
42
86
DAC
COUNTER
24
52

FIG. 3

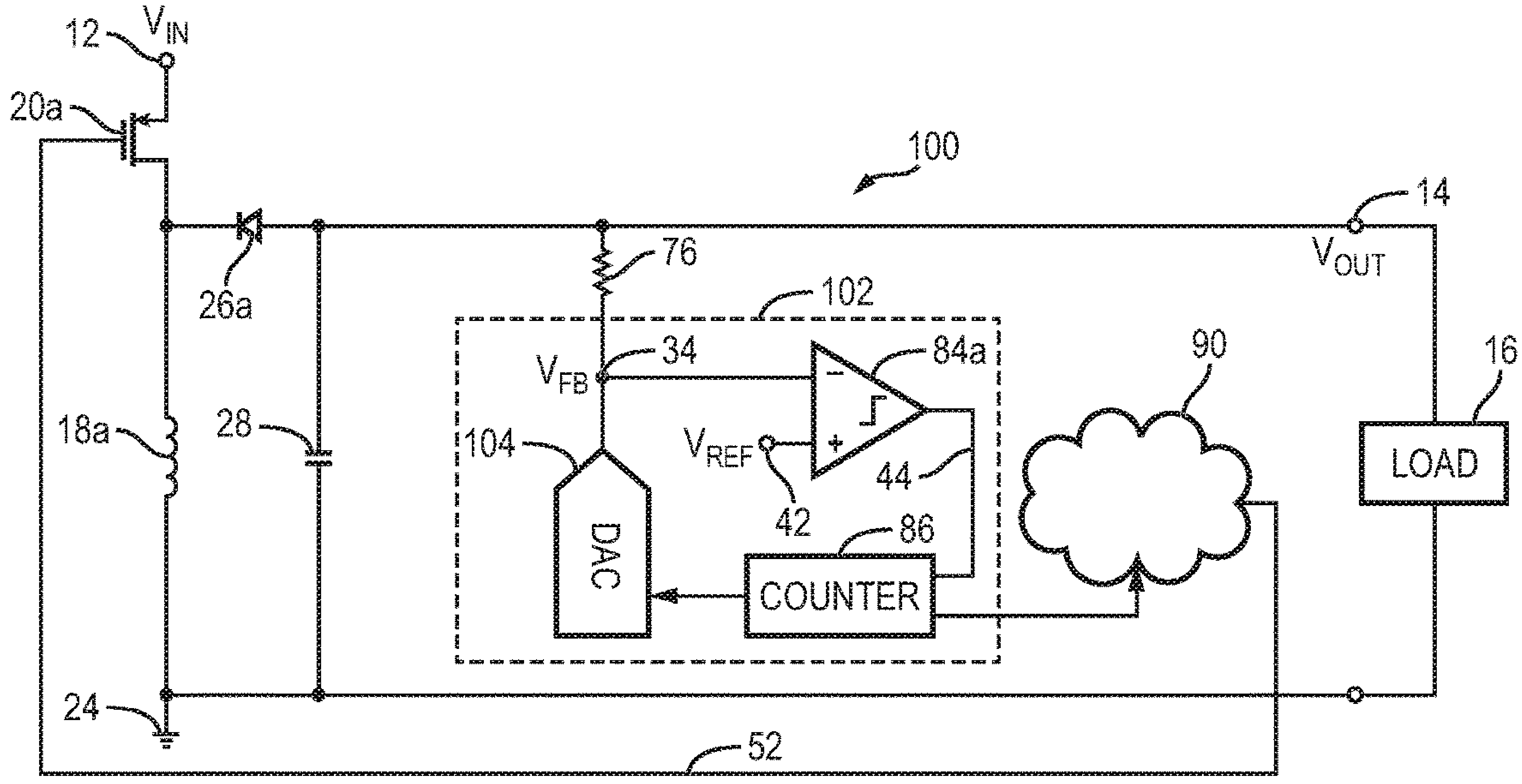

12
V_{IN}
20a
100
14
V_{OUT}
76
26a
102
V_{FB}
34
84a
90
16
LOAD
18a
28
104
V_{REF}
44
42
86
DAC
COUNTER
24
52

FIG. 4

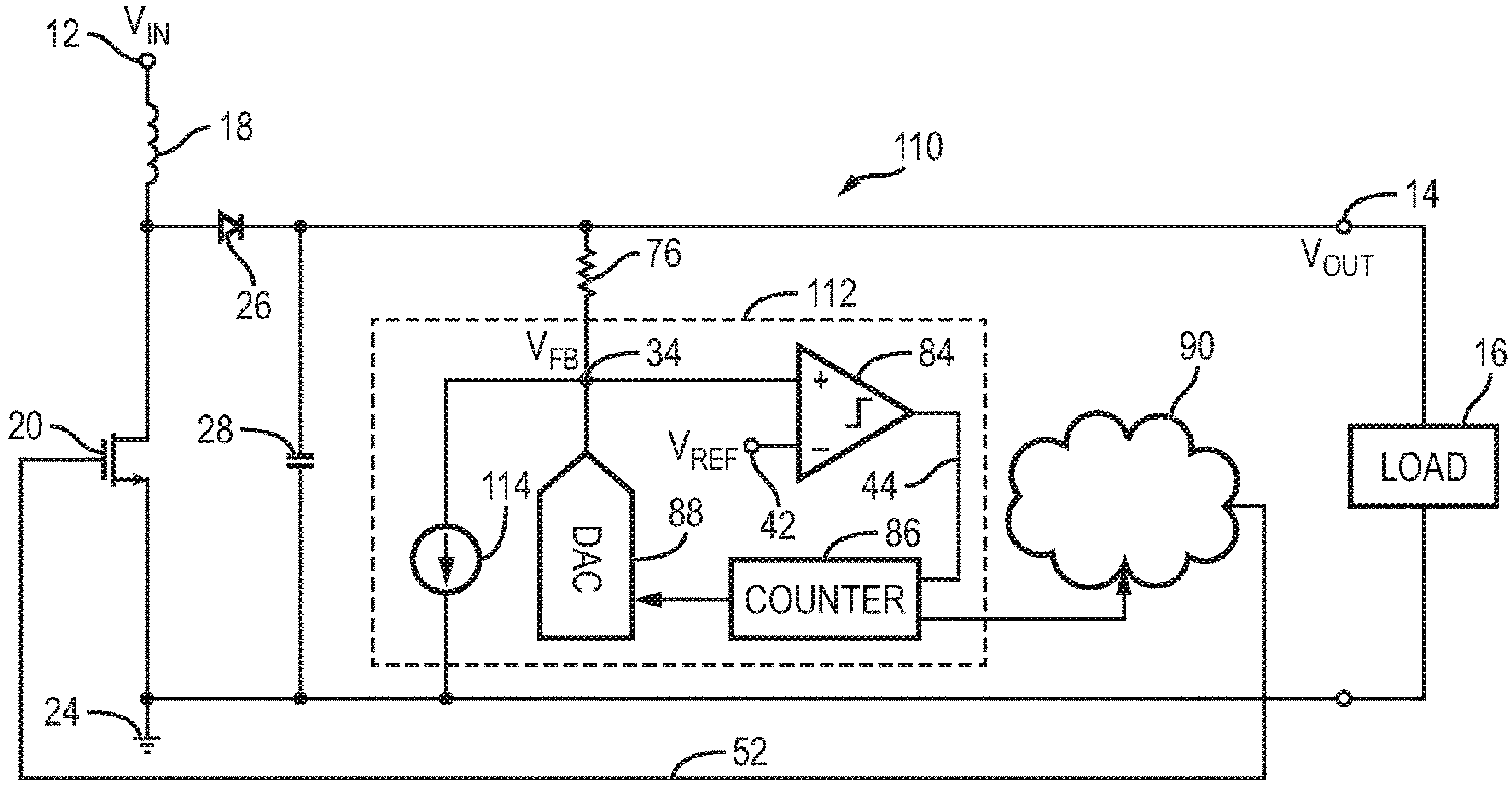

12
V_{IN}
18
110
14
V_{OUT}
26
76
112
V_{FB}
34
84
90
16
20
28
LOAD
V_{REF}
44
114
42
86
88
DAC
COUNTER
24
52

FIG. 5a

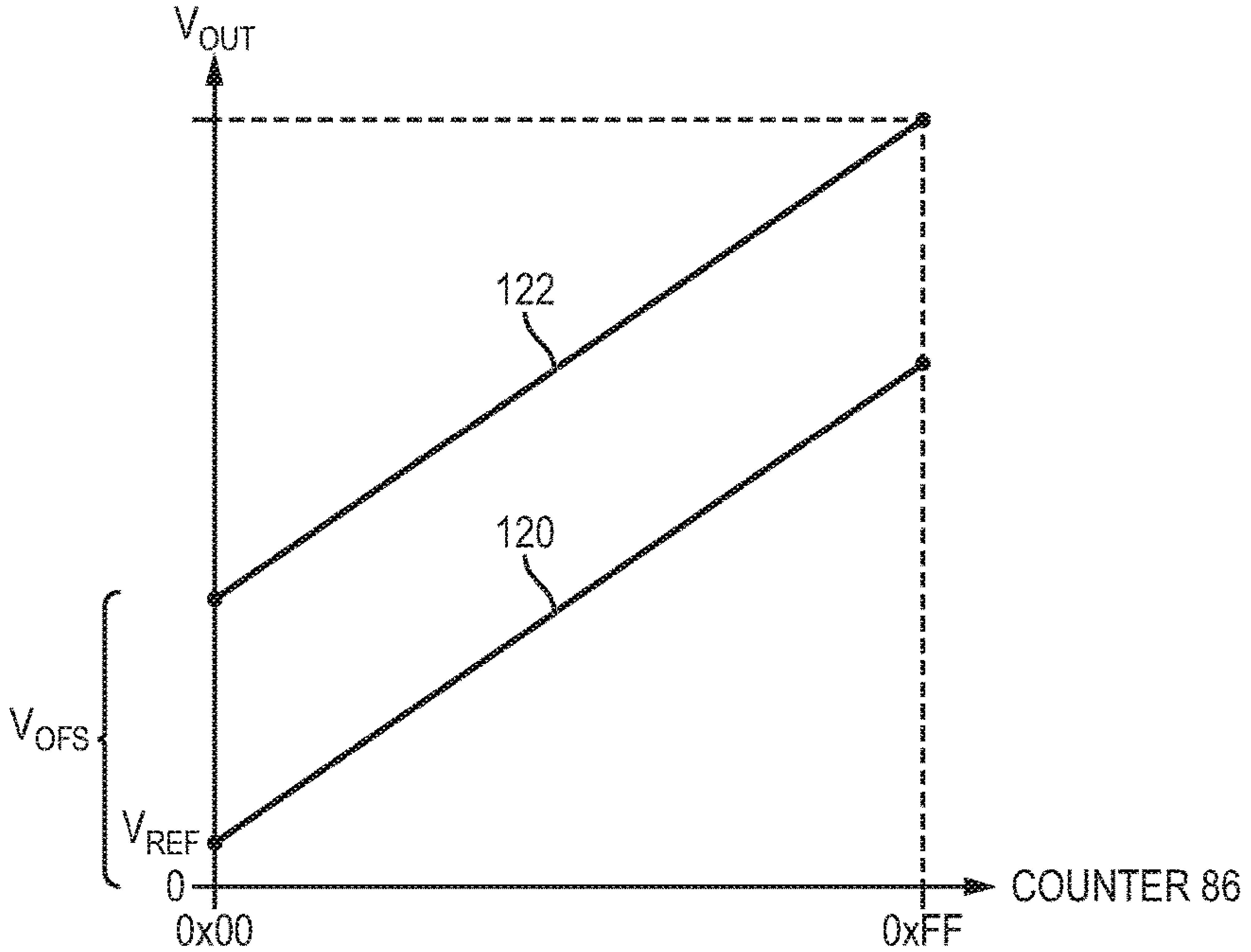

V_{OUT}
122
120
V_{OFS}
V_{REF}
0
0x00
0xFF
COUNTER 86

FIG. 5b

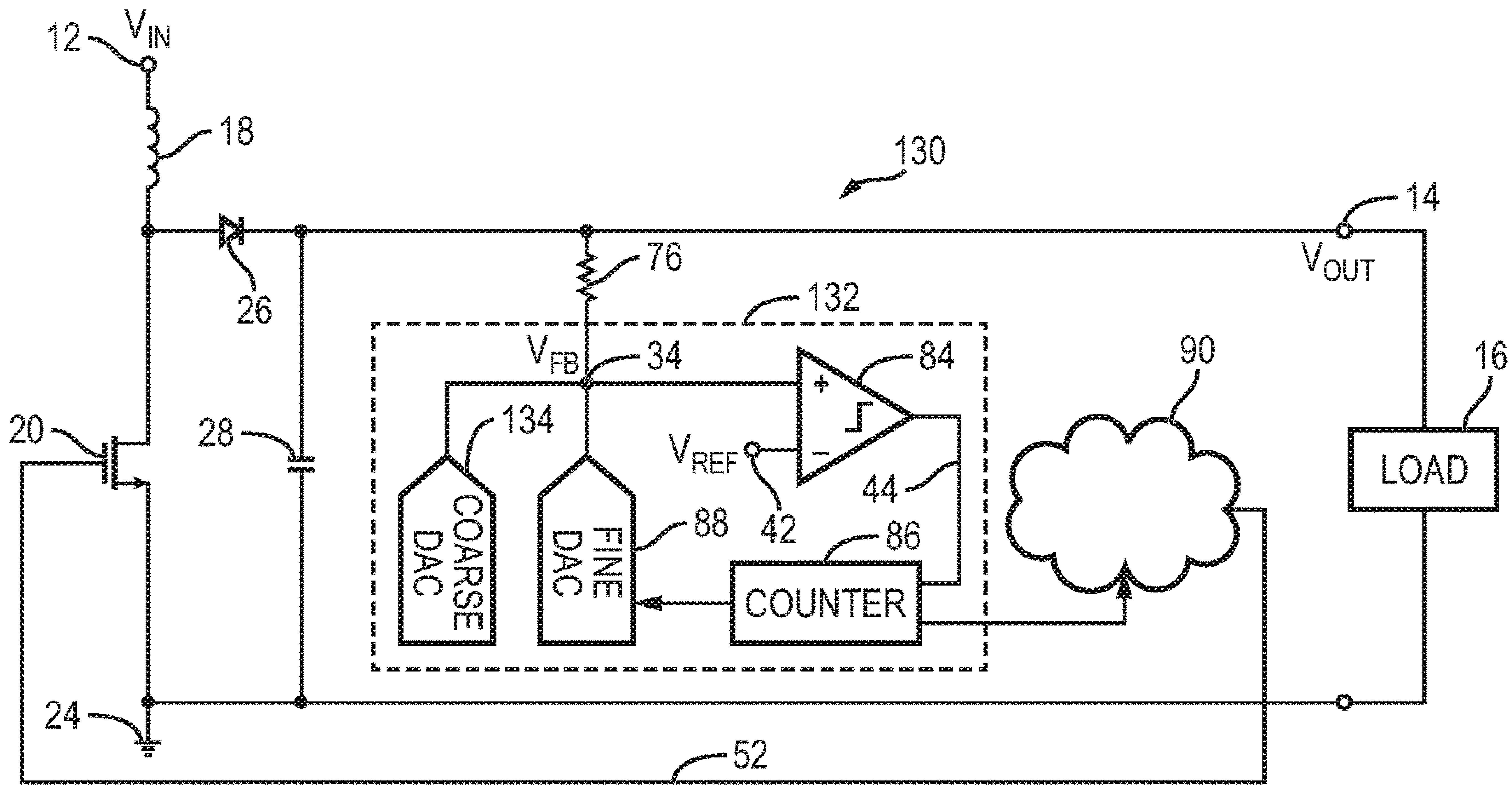

12
V_{IN}
18
130
14
V_{OUT}
26
76
132
V_{FB}
34
84
90
16
LOAD
20
28
134
V_{REF}
44
42
COARSE DAC
FINE DAC
88
86
COUNTER
24
52

FIG. 6a

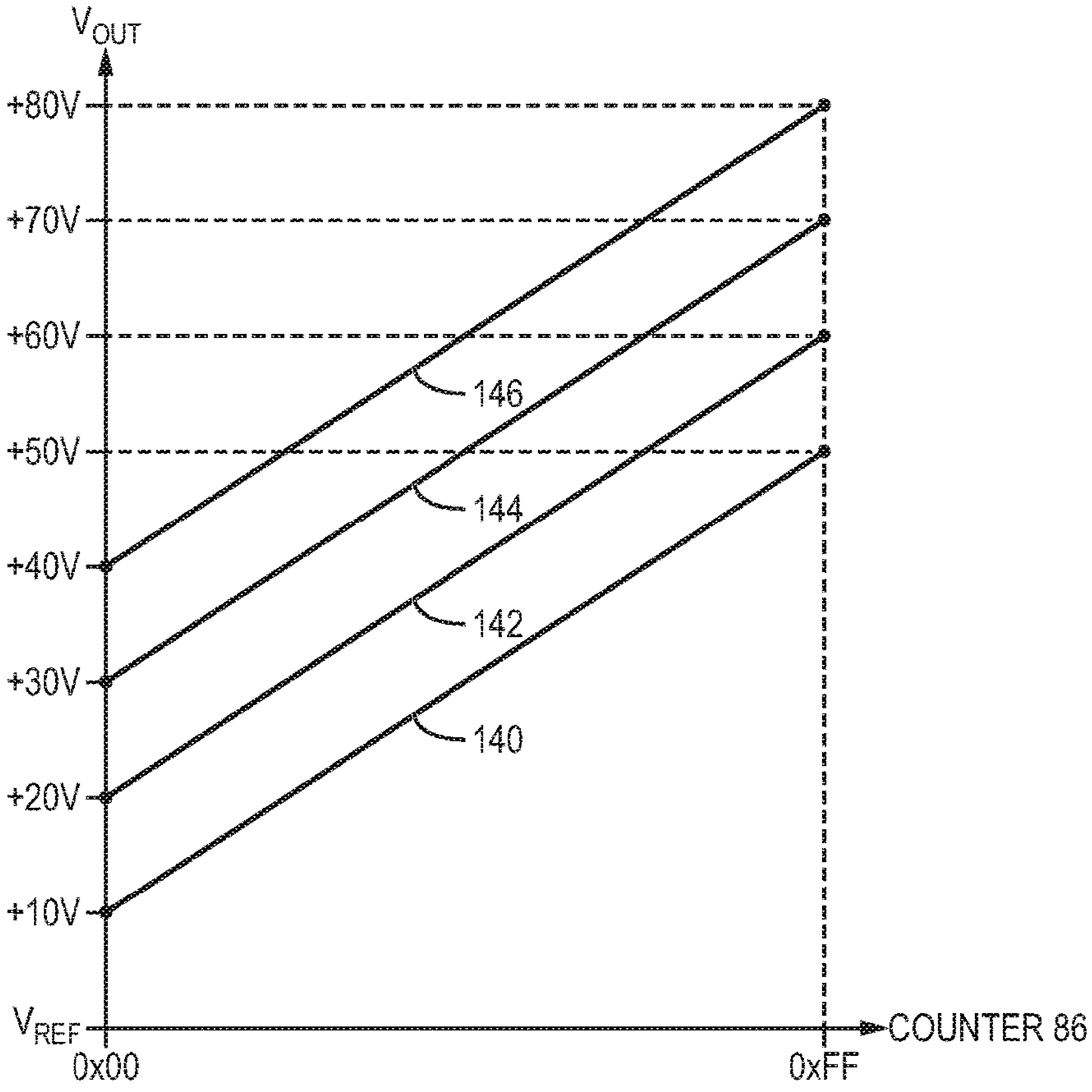

V_{OUT}
+80V
+70V
+60V
+50V
+40V
+30V
+20V
+10V
V_{REF}
146
144
142
140
0x00
0xFF
COUNTER 86

FIG. 6b

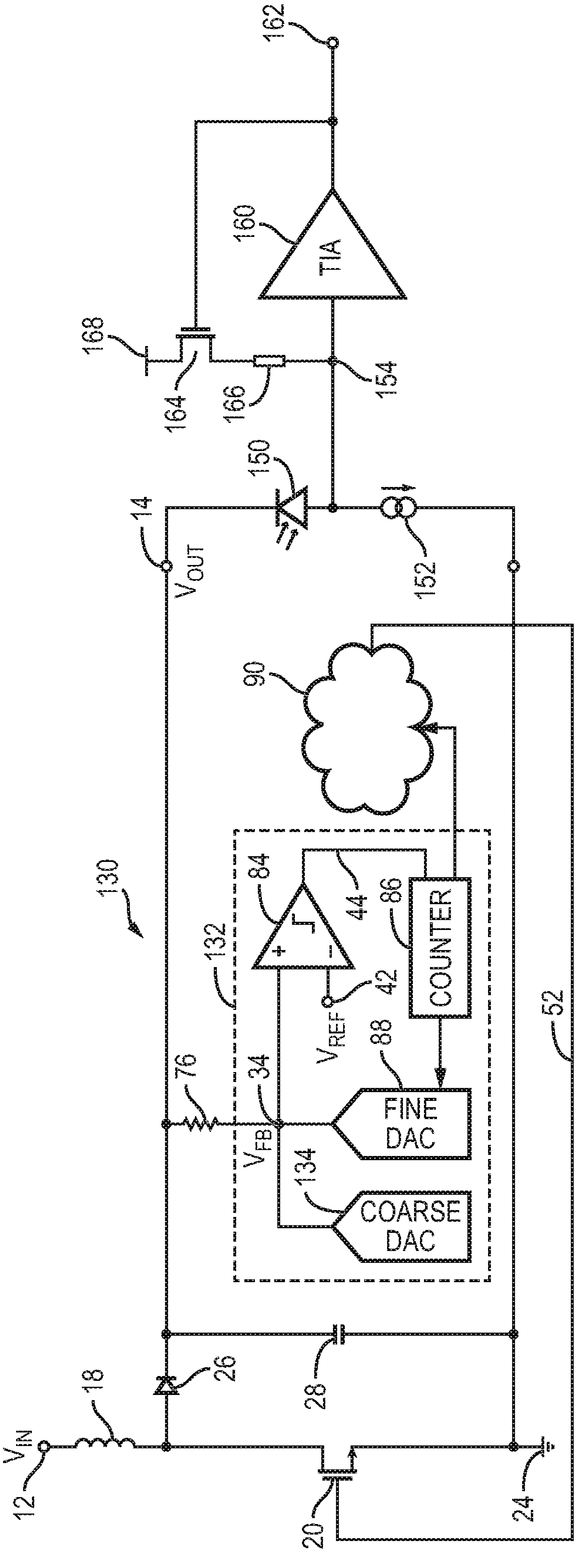

162
160
TIA
168
164
166
154
150
14
V_{OUT}
152
90
130
132
84
+
-
44
86
COUNTER
42
V_{REF}
88
34
76
V_{FB}
FINE DAC
134
COARSE DAC
52
26
18
V_{IN}
12
28
20
24

FIG. 7

CURRENT-BASED FEEDBACK CONTROL FOR VOLTAGE REGULATORS

FIELD OF THE INVENTION

The present invention relates in general to semiconductor devices and, more particularly, to a semiconductor device and method of current-based feedback control for voltage regulators.

BACKGROUND OF THE INVENTION

Semiconductor devices are commonly found in modern electronic products. Semiconductor devices vary in the number and density of electrical components. Discrete semiconductor devices generally contain one type of electrical component, e.g., light emitting diode (LED), small signal transistor, resistor, capacitor, inductor, and power metal-oxide-semiconductor field-effect transistor (MOSFET). Integrated semiconductor devices typically contain hundreds to millions of electrical components. Examples of integrated semiconductor devices include microcontrollers, microprocessors, charge-coupled devices (CCDs), solar cells, and digital micro-mirror devices (DMDs).

Semiconductor devices perform a wide range of functions such as signal processing, high-speed calculations, transmitting and receiving electromagnetic signals, controlling electronic devices, transforming sunlight to electricity, and creating visual projections for television displays. Semiconductor devices are found in the fields of entertainment, communications, power conversion, networks, computers, and consumer products. Semiconductor devices are also found in military applications, aviation, automotive, industrial controllers, and office equipment.

Many electronic devices are powered by voltage supplies that are not adequate for the semiconductor devices or other components within the electronic device. For instance, some electronic parts require 9 volts or 12 volts to operate, but are in an electronic device powered by two 1.5-volt batteries in series or 5 volts from a universal serial bus (USB) port. In other cases, a device is powered by a 5 or 12 volt source, but needs between 20 and 90 volts for a certain circuit element, e.g., an avalanche photodiode (APD).

In cases where input voltages need to be converted for powering of components, switch-mode power supplies (SMPS) are commonly used. Boost regulator **10** in FIG. **1** is one example of an SMPS topology. Boost regulator **10** receives an input voltage at V_{IN} node **12**, and converts the voltage to an output voltage at V_{OUT} node **14**. Electrical current flows through boost regulator **10** in two different paths. The first path is through inductor **18** and MOSFET **20** to ground node **24**, and the second path is through inductor **18** and diode **26** to V_{OUT} node **14**. Electrical current flows primarily through the first path when MOSFET **20** is turned on. The electrical current through inductor **18** stores energy in the inductor through magnetization of a ferric core. The electrical current through inductor **18** reaches a fairly high magnitude because MOSFET **20** creates a substantially short circuit between V_{IN} node **12** and ground node **24** through inductor **18**.

When a sufficient current through inductor **18** is reached, MOSFET **20** is shut off, and current flows instead through inductor **18** and diode **26** to V_{OUT} node **14**. The energy stored magnetically in inductor **18** during the first phase results in an electrical current through diode **26** larger than what load **16** would normally draw. The excess current through diode **26** raises the voltage potential at V_{OUT} node **14** above the voltage potential of V_{IN} node **12**. Capacitor **28** stores electrical charge not immediately usable by load **16**. As load **16** uses up the electrical energy stored in capacitor **28**, the voltage potential of V_{OUT} node **14** drops. When the voltage of V_{OUT} node **14** drops below a desired threshold, MOSFET **20** turns on and off again to inject more energy through diode **26** to V_{OUT} node **14**.

To determine when MOSFET **20** should turn on and off, a resistor voltage divider is formed from resistors **30** and **32** to create a feedback voltage at V_{FB} node **34**. The voltage potential at V_{FB} node **34** is given by equation 1.

$$V_{FB} = \frac{V_{OUT} * R_{32}}{R_{30} + R_{32}} \qquad \text{Equation 1}$$

The voltage potential at V_{FB} node **34** is proportional to the voltage potential at V_{OUT} node **14**, but reduced by the ratio of resistors **30** and **32**. Comparator **40** includes a first input coupled to V_{FB} node **34**, and a second input coupled to a reference voltage at V_{REF} node **42**. Comparator **40** has an output **44** that indicates whether the voltage potential of V_{FB} node **34** is above or below the voltage potential of V_{REF} node **42**.

Control logic **50** receives the output signal **44** from comparator **40**, and turns MOSFET **20** on and off using control signal **52** based on comparator output signal **44**. Several methods exist for controlling MOSFET **20** based on output signal **44**. In some embodiments, control logic **50** will increase a switching frequency or duty cycle of control signal **52** when V_{FB} falls below V_{REF}. In other embodiments, MOSFET **20** is switched at a predetermined frequency when V_{FB} node **34** is below V_{REF} node **42**, and remains off when V_{FB} node **34** is above V_{REF} node **42**.

An engineer designing a power supply based on voltage divider feedback generally buys a controller IC with comparator **40**, V_{REF} **42**, and control logic **50**. Given V_{REF} **42** set by the controller IC manufacturer, the engineer selects resistance values of resistor **30** and resistor **32** to set the voltage potential that V_{OUT} node **14** will be regulated to. The voltage potential at V_{OUT} node **14** will settle at a voltage indicated by equation 2.

$$V_{OUT} = \frac{V_{REF} * (R_{30} + R_{32})}{R_{32}} \qquad \text{Equation 2}$$

Using a resistive voltage divider for feedback creates a voltage at V_{FB} node **34** that is acceptable for input to comparator **40**. However, the resistive voltage divider is not a flexible approach. The voltage divider is not easily calibrated to provide high-resolution voltage control in a limited voltage range of V_{OUT} node **14**. Moreover, the voltage divider not only reduces voltage from V_{OUT} node **14** to V_{FB} node **34**, but also reduces the magnitude of changes in voltage. The reduction in magnitude of voltage changes from V_{OUT} node **14** to V_{FB} node **34** makes the control circuitry less robust against noise.

Therefore, a need exists for a more flexible feedback mechanism for voltage regulators.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a voltage regulator that creates a feedback voltage using a voltage divider;

FIG. **2** illustrates a voltage regulator that creates a feedback voltage using electrical current through a resistor;

FIG. **3** illustrates a voltage regulator that creates a feedback voltage using a current-sink digital-to-analog converter (DAC) to control the magnitude of electrical current through a resistor;

FIG. **4** illustrates a current-source DAC used to regulate a negative voltage potential;

FIGS. **5***a* and **5***b* illustrate a current source in parallel with the current-sink DAC to create a voltage offset;

FIGS. **6***a* and **6***b* illustrate a coarse-adjustable DAC in parallel with a fine-adjustable DAC to allow the voltage regulator to be calibrated for different uses; and

FIG. **7** illustrates a voltage regulator powering an avalanche photodiode.

DETAILED DESCRIPTION OF THE DRAWINGS

The present invention is described in one or more embodiments in the following description with reference to the figures, in which like numerals represent the same or similar elements. While the invention is described in terms of the best mode for achieving the invention's objectives, those skilled in the art will appreciate that the description is intended to cover alternatives, modifications, and equivalents as may be included within the spirit and scope of the invention as defined by the appended claims and the claims' equivalents as supported by the following disclosure and drawings.

FIG. **2** illustrates voltage regulator **70** with a feedback signal at V_{FB} node **34** created by resistor **76** and current source **78** rather than a voltage divider. Resistor **76** and current source **78** are coupled in series between V_{OUT} node **14** and ground node **24**. Current source **78** draws electrical current from V_{OUT} node **14** to ground node **24** through resistor **76**. The current through resistor **76** results in a voltage drop from V_{OUT} node **14** to V_{FB} node **34** that is equivalent to the value of the resistor multiplied by the amount of current. Electrical current through resistor **76** can be considered equal to the value of current being drawn by current source **78** for all practical purposes, even though in practice there may be a negligible difference that may or may not be detectable.

Due to electrical current through resistor **76** being practically a fixed value, the voltage drop across resistor **76** is also fixed. V_{OUT} node **14** has a voltage potential that is above V_{FB} node **34** by a fixed magnitude. The voltage potential of V_{FB} node **34** relative to V_{OUT} node **14** is given by equation 3, where I_{78} indicates the magnitude of current source **78**, and R_{76} indicates the resistance value of resistor **76**.

$$V_{FB}=V_{OUT}-(I_{78}*R_{76}) \qquad \text{Equation 3:}$$

When regulator **70** is turned on, V_{FB} node **34** settles at the same voltage potential as V_{REF} node **42** because those are the two values being input to comparator **40**. Therefore, output voltage of regulator **70** at V_{OUT} node **14** is set by configuring the magnitude by which V_{FB} node **34** is below V_{OUT} node **14** with the design parameters of resistor **76** and current source **78**. In one embodiment, a designer of a power supply buys an integrated circuit (IC) package with comparator **40**, V_{REF} node **42**, and current source **78** integrated into the package. The designer knows the values of current source **78** and V_{REF} **42** built into the IC, and selects a resistance value for resistor **76** to create a desired voltage drop across the resistor such that V_{REF} **42** plus the voltage drop equals a desired voltage potential of V_{OUT} node **14**. The regulated voltage at V_{OUT} node **14** will settle to a value proportional to the selected resistance value for resistor **76**, as given by equation 4.

$$V_{OUT}=V_{REF}+(I_{78}*R_{76}) \qquad \text{Equation 4:}$$

As an example, if the manufacturer of a controller IC sets V_{REF} node **42** at 5 volts and current source **78** at 50 milliamps, the power supply designer could set the value of resistor **76** at 140 ohms to generate V_{OUT} node **14** as a 12-volt output. Ohm's law dictates that the voltage drop across resistor **76** will be current (50 milliamps, set by IC manufacturer) multiplied by resistance (140 ohms, selected by the power supply designer). Therefore, the voltage across resistor **76** in the example will be 7 Volts. Control logic **50** will be maintaining V_{FB} node **34** at approximately the same voltage potential as V_{REF} node **42** (5 volts), so V_{OUT} node **14** will be held at approximately 5 volts (the voltage of V_{REF}) plus 7 volts (the voltage across resistor **76**), i.e., 12 volts.

In some embodiments, the controller IC manufacturer provides a V_{FB} node **34** terminal on the package, which is directly coupled to current source **78** and comparator **40** within the package. The designer of power supply **70** selects the desired resistance value and solders resistor **76** onto a printed circuit board (PCB) or other substrate adjacent to the controller IC and electrically connected to the V_{FB} node **34** terminal of the controller IC.

Current through resistor **76** is relatively constant, which means that the voltage difference between V_{OUT} node **14** and V_{FB} node **34** is relatively constant. There is a direct relationship between the two voltages, such that voltage fluctuations of V_{OUT} node **14** are observed at V_{FB} node **34** with substantially the same magnitude. Because the magnitude of voltage changes is not reduced between V_{OUT} node **14** and V_{FB} node **34**, the feedback voltage generated with resistor **76** and current source **78** is more robust to noise compared to a voltage divider. In addition, the offset and gain of comparator **40** are less critical, enabling the use of simpler and cheaper comparators.

FIG. **3** illustrates a voltage regulator **80** with a feedback circuit **82**. Feedback circuit **82** comprises comparator **84**, a counter **86**, and a current-sink DAC **88**. Comparator **84** compares V_{REF} node **42** to V_{FB} node **34**, as above, and generates an output signal **44**. The output signal **44** controls whether counter **86** increments or decrements.

DAC **88** is a current sink that pulls current from V_{OUT} node **14** through resistor **76**, with the magnitude of current being controlled by the value stored in counter **86**. The voltage potential at V_{FB} node **34**, in turn, is controlled by the magnitude of current being drawn by DAC **88**. Feedback circuit **82** operates similarly to an analog-to-digital converter (ADC). Counter **86** provides a linear representation of the voltage potential of V_{OUT} node **14**. A digital value in counter **86** will settle at a value proportional to an analog voltage potential at V_{OUT} node **14**, and can be used to control output voltage with a purely digital controller. The voltage at V_{OUT} node **14** is given by equation 5. In equation 5, counter represents the digital value stored in counter **86**, and I_{LSB} represents the change in magnitude of current drawn by DAC **88** by changing the least significant bit of the counter.

$$V_{OUT}=V_{REF}+(\text{counter}*I_{LSB}*R_{76}) \qquad \text{Equation 5:}$$

As voltage at V_{OUT} node **14** rises, the voltage potential at V_{FB} node **34** will rise by an approximately equal magnitude. Comparator **84** will indicate that V_{FB} node **34** is at a higher voltage potential than V_{REF} node **42**, and cause counter **86** to count upward. The rising value in counter **86** increases the magnitude of current drawn by DAC **88** through resistor **76**, which increases the voltage drop across the resistor. Counter **86** will count up until the current drawn by DAC **88** is sufficient to reduce the voltage potential at V_{FB} to be less than V_{REF}. The amount by which counter **86** must count up is proportional to the voltage change at V_{OUT} node **14**.

As voltage at V_{OUT} node **14** falls, the voltage potential at V_{FB} node **34** falls by an approximately equal magnitude. Comparator **84** will indicate that the V_{FB} node **34** is at a lower voltage potential than V_{REF} node **42**, and cause counter **85** to count downward. The falling value in counter **86** reduces the magnitude of current drawn by DAC **88** through resistor **76**, which reduces the voltage drop across the resistor. Counter **86** will count down until the current drawn by DAC **88** is low enough to increase the voltage of V_{FB} node **34** to a greater value than V_{REF} node **42**. The amount by which the value in counter **86** falls is proportional to the drop in voltage potential at V_{OUT} node **14**.

As the voltage potential of V_{OUT} node **14** fluctuates, counter **86** moves proportionally. The value in counter **86** is a digital value proportional to a voltage potential at V_{OUT} node **14**. Control logic **90** reads the digital value in counter **86** and uses the knowledge of the output voltage to control MOSFET **20**. If the value in counter **86** indicates that V_{OUT} node **14** is at a lower than desired voltage potential, control logic **90** increases the frequency or duty cycle of switching MOSFET **20** to bring up the voltage of V_{OUT} node **14**. Control logic **90** observes the value in counter **86** to return the switching frequency to a lower value once the voltage potential at V_{OUT} node **14** returns to the desired level.

One advantage of utilizing a current DAC and single resistor architecture rather than a dual-resistor voltage divider is that negative voltages can be regulated by inverting the polarity of the comparator and mirroring the DAC to a source DAC rather than a sink DAC. On the other hand, the prior art architecture generally needs an additional fixed voltage for the voltage divider. Therefore, an additional pin on the controller IC is usually required to regulate negative voltages.

Power regulator **100** in FIG. **4** is configured to regulate V_{OUT} node **14** to a negative voltage potential. The polarity of diode **26** has been reversed, and the diode is labelled as diode **26***a*. The placement of inductor **18** and MOSFET **20** has been reversed, and the respective parts are labelled as **18***a* and **20***a*. MOSFET **20***a* is a P-channel device, whereas MOSFET **20** was an N-channel device.

FIG. **4** illustrates a feedback circuit **102** with sink DAC **88** replaced with source DAC **104**. Source DAC **104** outputs an electrical current through resistor **76** to V_{OUT} node **14** proportional to the value in counter **86**. In some embodiments, a convertible DAC can be implemented that is configurable to be either a sink DAC or a source DAC, allowing a single controller IC to regulate positive or negative voltages. Comparator **84***a* is the same hardware component as comparator **84** above in some embodiments, but simply has the input polarity switched. That is, V_{REF} node **42** is coupled to the inverting input rather than the non-inverting input of comparator **84**. The coupling of comparator **84** inputs can be controlled electronically to allow a single comparator to be configured either for regulation of positive or negative voltages. In other embodiments, comparator **84** is configured for regulating negative voltages by inverting the output rather than swapping the inputs.

The voltage potential calculations for V_{FB} node **34** and V_{OUT} node **14** of negative voltage regulator **100** in FIG. **4** are similar to the positive regulator in FIG. **3**. The feedback voltage is given by equation 6, and the regulated voltage is given by equation 7. Again, when regulator **100** settles, the voltage potentials of V_{FB} node **34** and V_{REF} node **42** will be substantially equal.

$$V_{FB}=V_{OUT}+(\text{counter}*I_{LSB}*R_{76}) \qquad \text{Equation 6:}$$

$$V_{OUT}=V_{REF}-(\text{counter}*I_{LSB}*R_{76}) \qquad \text{Equation 7:}$$

Feedback circuit **102** in FIG. **4** operates in substantially the same manner as feedback circuit **82** in FIG. **3**, but is reconfigured to regulate a negative voltage instead of a positive voltage.

FIG. **5***a* illustrates a power regulator **110** with feedback circuit **112**. Feedback circuit **112** includes current-sink DAC **88** as in FIG. **3**, and a current source **114** coupled in parallel with the DAC. Comparator **84**, counter **86**, and DAC **88** operate in substantially the same manner as in FIG. **3** to populate counter **86** with a digital value proportional to the voltage potential at V_{OUT} node **14**.

Current source **114** is coupled to V_{FB} node **34** in parallel with current DAC **88**, and draws a fixed amount of current through resistor **76** regardless of counter **86**. Current source **114** creates a voltage potential offset because of the additional current through, and voltage drop across, resistor **76**. Without current source **114**, when counter **86** contains the value zero, DAC **88** draws no current and the voltage potential at V_{FB} node **34** equals the voltage potential at V_{OUT} node **14**. V_{OUT} node **14** is regulated to the voltage potential of V_{REF} node **42**, because that is the voltage potential when V_{FB} node **34** equals V_{REF}. The maximum regulated voltage potential without current source **114** is given by equation 7, with counter **86** being at the maximum value, e.g., 0xFF in hexadecimal for an 8-bit DAC.

Line **120** in FIG. **5***b* illustrates an example plot of DAC **88** value on the horizontal axis versus output voltage on the vertical axis. A linear relationship is illustrated, with plot **120** beginning at the voltage potential of V_{REF} node **42** and growing linearly as counter **86** counts from 0x00 to 0xFF. FIG. **5***b* presumes an 8-bit counter, but other bit-widths are used in other embodiments.

The controller IC with feedback circuit **82** in FIG. **3** can be accurately regulated to voltages near V_{REF}, which for a lot of use cases is not needed, and has relatively low maximum regulation voltages that may not be sufficient for all use cases. Adding current source **114** in parallel increases the voltage drop across resistor **76**, and thus raises the voltage potential of V_{OUT} node **114**, for all values of counter **86**. Plot **122** in FIG. **5***b* illustrates the counter **86** value versus output voltage with current source **114** added. V_{OFS} indicates the difference in output voltage between a given value of counter **86** with and without current source **114**. V_{OFS} is given by equation 8, where I_{114} is the magnitude of electrical current that current source **114** is drawing.

$$V_{OFS}=I_{114}*R_{76}+V_{REF} \qquad \text{Equation 8:}$$

Adding current source **114** shifts the voltage potential at V_{OUT} node **14** up by V_{OFS} for a given value of counter **86**, thus raising both the minimum regulable output voltage and the maximum regulable output voltage. The range provided by line **122** in FIG. **5***b* is a more useful range for many purposes. For instance, an avalanche photodiode may need a voltage in the range of 30 to 50 volts, which is totally within the vertical range of line **122**, while the regulator without current source **114** only allows regulation up to say 40 volts.

FIG. **6***a* illustrates a more flexible power regulator **130**, where feedback circuit **132** has a coarse DAC **134** added in parallel with DAC **88**. Coarse DAC **134** is an adjustable current source without the same level of fine adjustment that DAC **88** offers. While an 8-bit counter **86** allows for 256 different values for the current drawn by DAC **88**, coarse DAC may only have four or five different settings. In one embodiment, coarse DAC **134** is simply a plurality of current sources **114** coupled in parallel, and enablable in any combination to achieve a desired V_{OFS}.

FIG. **6***b* illustrates a plurality of possible counter **86** versus V_{OUT} plots depending on the value selected for coarse DAC **134**. Line **140** shows the coarse DAC sinks current equivalent to a 10 volt drop across resistor **76**, allowing fine DAC **88** to adjust between 10 volts and 50 volts over V_{REF} node **42**. Line **142** shows coarse DAC **134** set to a 20 volt offset, allowing fine DAC **88** to adjust from 20 volts to 60 volts above V_{REF}. Line **144** illustrates coarse DAC **134** with an offset of 30 volts, allowing fine DAC **88** to adjust from 30 volts to 70 volts above V_{REF}. Line **146** illustrates coarse DAC **134** set to a 40 volt offset, allowing fine DAC **88** to adjust between 40 volts and 80 volts above V_{REF}. In other embodiments, additional settings of coarse DAC **134** are used to apply any desired offset to the fine adjustment range of fine DAC **88**. Coarse DAC **134** allows the resolution of fine DAC **88** to be shifted to a desired range. The regulated output voltage of regulator **130** is given by equation 9.

$$V_{OUT}=(I_{134}+I_{88})*R_{76}+V_{REF} \qquad \text{Equation 9:}$$

One common use of the disclosed power regulators is for providing power to avalanche photodiode (APD) circuits as shown in FIG. **7**. Load **16** includes an avalanche photodiode **150** and current source **152** coupled in series between V_{OUT} node **14** and ground node **24**. A light signal, typically delivered via a fiber optic cable, hits APD **150** and modifies the electrical resistance of the APD, which changes the voltage potential at circuit node **154**. Transimpedance amplifier (TIA) **160** has an input coupled to circuit node **154**, and an output at circuit node **162**. A feedback path of TIA **160** comprises a MOSFET **164** and resistor **166** coupled between V_{DD} **168** and circuit node **154**. Semiconductor devices coupled to output node **162** receive the information from the fiber optic cable as an electrical signal.

Depending on the manufacturer and model of a particular APD **160** that is selected, the APD will require that the voltage potential at V_{OUT} node **14** fall within a different range that can vary significantly. With the prior art voltage divider approach, the wider the spread of operational voltage of different APDs, the worse the resolution of the control voltage. However, the adjustment provided by coarse DAC **134** means that the fine adjustment of DAC **88** can be moved around if a particular APD **160** selected requires a different voltage range. The voltage of V_{FB} node **34** always settles to be substantially equal to the voltage of V_{REF} node **42**, so any voltage range can be achieved as long as the current of coarse DAC **134** can be made high enough.

Another benefit of the above implementation that includes digital-to-analog converters is that the DACs can be used for other purposes if not needed for regulator control logic. Many of the ICs that include the control logic may be used in situations where an external charge pump for controlling V_{OUT} node **14** is not needed. In that case, the user can still use the DAC for other purposes.

While one or more embodiments of the present invention have been illustrated in detail, the skilled artisan will appreciate that modifications and adaptations to those embodiments may be made without departing from the scope of the present invention as set forth in the following claims.

What is claimed:

1. A method of making a voltage regulator, comprising:
- providing a comparator including a reference voltage coupled to a first input of the comparator;
- coupling a first current source to a second input of the comparator, wherein the first current source includes a digital-to-analog converter (DAC);
- coupling a counter between an output of the comparator and an input of the DAC; and
- coupling a resistor to the second input of the comparator.

2. The method of claim **1**, further including coupling the second input of the comparator to an output voltage node through the resistor.

3. The method of claim **2**, further including coupling the second input of the comparator to a ground voltage node through the first current source.

4. The method of claim **1**, further including modifying a switching frequency of the voltage regulator based on an output of the comparator.

5. The method of claim **1**, further including providing a second current source coupled in parallel with the first current source, wherein the first current source is fine adjustable and the second current source is coarse adjustable.

6. The method of claim **1**, wherein the voltage regulator includes a boost topology.

7. A method of making a voltage regulator controller, comprising:
- providing a comparator including a reference voltage coupled to a first input of the comparator;
- coupling a first current source to a second input of the comparator; and
- providing a second current source coupled in parallel with the first current source, wherein the first current source is fine adjustable and the second current source is coarse adjustable.

8. The method of claim **7**, wherein the first current source is a digital-to-analog converter (DAC).

9. The method of claim **8**, further including providing a counter coupled between an output of the comparator and an input of the DAC.

10. The method of claim **7**, further including coupling a voltage output terminal of the voltage regulator controller to the second input of the comparator.

11. A voltage regulator, comprising:
- a comparator including a reference voltage coupled to a first input of the comparator;
- a first current source coupled to a second input of the comparator;
- a second current source coupled in parallel with the first current source, wherein the first current source is fine adjustable and the second current source is coarse adjustable; and
- a resistor coupled to the second input of the comparator.

12. The voltage regulator of claim **11**, wherein the voltage regulator includes a voltage output node coupled to the second input of the comparator through the resistor.

13. The voltage regulator of claim **12**, further including a ground node, wherein the ground node is coupled to the second input of the comparator through the first current source.

14. The voltage regulator of claim **11**, wherein the first current source is a digital-to-analog converter (DAC).

15. The voltage regulator of claim **14**, further including a counter coupled to an output of the comparator to control the DAC.

16. The voltage regulator of claim **11**, wherein the voltage regulator is a boost topology.

17. A voltage regulator controller, comprising:

a comparator including a reference voltage coupled to a first input of the comparator;

a first current source coupled to a second input of the comparator, wherein the first current source is a digital-to-analog converter (DAC); and

a counter coupled between an output of the comparator and an input of the DAC.

18. The voltage regulator controller of claim **17**, further including a second current source coupled in parallel with the first current source.

19. The voltage regulator controller of claim **18**, wherein the first current source is fine adjustable and the second current source is coarse adjustable.

20. The voltage regulator controller of claim **17**, wherein a voltage output terminal of the voltage regulator controller is coupled to the second input of the comparator.

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